SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

AD-A215 085

1b. RESTRICTIVE MARKINGS

3. DISTRIBUTION/AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

2

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFOSR-TR- 89-1462

6a. NAME OF PERFORMING ORGANIZATION
George Washington University
School of Engineering and

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
AFOSR

6c. ADDRESS (City, State, and ZIP Code)
Applied Science
Washington, D.C. 20052

7b. ADDRESS (City, State, and ZIP Code)
BLDG 410
BAFB DC 20332-6448

8a. NAME OF FUNDING/SPONSORING ORGANIZATION
AFOSR

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AFOSR-76-3099

8c. ADDRESS (City, State, and ZIP Code)
BLDG 410
BAFB DC 20332-6448

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.
61102F	2308	B2	

11. TITLE (Include Security Classification)
FRACTURE AND FATIGUE CHARACTERIZATION OF AIRCRAFT STRUCTURAL MATERIALS UNDER BIAXIAL LOADING

12. PERSONAL AUTHOR(S)
D.L. Jones/ J. Eftis

13a. TYPE OF REPORT
Final

13b. TIME COVERED
FROM Oct 78 TO Dec 79

14. DATE OF REPORT (Year, Month, Day)
December 1979

15. PAGE COUNT
34

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE (Include Area Code)
767-4987

22c. OFFICE SYMBOL
NA

FRACTURE AND FATIGUE CHARACTERIZATION OF AIRCRAFT STRUCTURAL MATERIALS UNDER BIAXIAL LOADING

FINAL [redacted] Scientific Report

October 1978 - December 1979

D. L. Jones and J. Eftis

Research Grant AFOSR-76-3099

Submitted to

Air Force Office of Scientific Research

Building 410

Bolling Air Force Base

Washington, D.C. 20332

School of Engineering and Applied Science

The George Washington University

Washington, D.C. 20052

INTRODUCTION

Although many components of aircraft and aerospace structures are subjected to biaxial applied loads, the effects on the fracture process of loads applied parallel to an existing crack have not yet been fully appreciated. Although this problem was addressed in the first two papers published on fracture mechanics by Griffith [1,2], it was not treated adequately then and, in fact, was treated differently in these two papers. The matter still has not been resolved conclusively although two research grants dealing with this matter, sponsored by the Air Force [3,4], have added considerable insight into this matter. This report summarizes the results of the third year of AFOSR Grant 76-3099, Fracture and Fatigue of Aircraft Structural Materials Under Biaxial Loading, which was initiated for the purpose of examining both the theoretical and experimental aspects of this problem.

During the first two years of this grant a considerable amount of analytical work was performed and an experimental test facility was developed and employed for a number of fracture tests on biaxial specimens. The analytical work was responsible for the publication of five papers in appropriate journals and the preparation of one additional paper for publication. These papers discussed various implications of biaxially applied loads on the crack-tip stress field, the stress intensity factor, the angle of initial crack extension, and

the critical or fracture loads. Several different geometries were examined including center cracks aligned with and at an angle to the load axes, shear panels, double and multiple cracked bodies. For the experimental part of the program, the test facility was designed and fabricated and a number of test series were performed on specimens containing flat cracks oriented with one of the load axes. Biaxial fracture toughness tests were performed on 7075-T6 and 2024-T3 aluminum alloys with the cracks oriented both parallel and perpendicular to the rolling direction and on plexiglass sheets. In addition, the effect of in-phase biaxial cyclic loads on fatigue crack growth rates in 2024-T3 aluminum was examined in four tests. Although the fatigue tests were performed in the second year of this grant, the data reduction was not completed until later. The results of all of these research tasks were summarized in the first two progress reports submitted to AFOSR.

During the third year of this program, additional research has been performed on both the analytical and experimental aspects of the problem. A careful re-examination of the energy approach first developed by Griffith has been performed and used as a basis for predicting the effects of biaxial applied loads on the breaking strength of cracked bodies. Then these predictions were compared with the results of tests performed under this research program and elsewhere [5], with the result that Griffith's first paper resulted in better agreement with

the experimental results than his "corrected" paper in 1924 [2]. These results and conclusions have been submitted for publication but have not as yet been accepted.

Some additional studies have been made into the effect of biaxial applied loads on fatigue crack growth rates. The procedure followed was to examine analytical and experimental results previously published and to identify fundamental parameters controlling the fatigue crack growth rates and the effects of biaxial applied loads on them.

The experimental portion of this research program was productive during the third year of this grant, with a number of static and fatigue tests completed. In addition, the data taken during the present year, along with much of the data taken previously, has been further reduced and correlated with the theory and other experimental results.

Additional fracture toughness tests have been performed on plexiglass sheets having cracks aligned with one of the load axes and on 7075-T6 sheets with the cracks oriented at 45 degrees to either load axis. In addition to the four fatigue crack growth rate tests performed on 2024-T3 last year, four fatigue crack growth rate tests were performed on 7075-T6 specimens, with load biaxiality ratios of $k = 0$, 0.5, 1.0, and 1.5. The results of these tests and the further reduction of the data from earlier tests will be presented in this report.

SUMMARY OF ANALYTICAL PROGRESS

In the introduction to this report it was noted that the analytical work had two different directions during this reporting period. These two directions involved a careful re-examination of the effects of biaxial loads on the energy approach to fracture developed by Griffith and a study into the effects of biaxial loads on fatigue crack growth rates. The results obtained from both of these efforts are discussed in this section.

Biaxial Load Effects on the Griffith Problem

The "so-called" Griffith problem refers to the energy analysis of an infinite body containing an internal line crack subjected to loads along the outer boundaries. Griffith included some considerations of the effects of biaxial loads in his work but his analysis was both incomplete and only partially correct[5]. Griffith showed in his first paper [1] that the change in strain energy U_a, associated with the insertion of a line crack of length 2a in an infinite body (c.f. Fig. 1) was given as

$$U_a = \frac{\sigma^2 \pi a^2}{8\mu}(3-\kappa). \tag{1}$$

In Eq. (1), σ is the applied stress at infinity, μ is the elastic shear modulus, ν is Poisson's ratio, and

$$K = \begin{cases} \dfrac{3-\nu}{1+\nu} & \text{plane stress conditions} \\ 3-4\nu & \text{plane strain conditions.} \end{cases}$$

Although Eq. (1) is correct only for equal tension-tension loadings, k=1, Griffith assumed that it was equally valid for other biaxial ratios.

In 1924, Griffith published a second paper in which he modified Eq. (1) to the form

$$U_a = \frac{\sigma^2 \pi a^2}{a\mu}(1+\kappa) \tag{2}$$

with the following explanation given for the change:

> "A solution of this problem was given in a paper read in 1920 but in the solution there given the calculation of the strain energy was erroneous, in that the expressions used for the stresses gave values at infinity differing from the postulated uniform stress at infinity by an amount which, though infinitesimal, yet made a finite contribution to the energy when integrated round the infinite boundary. This difficulty has been overcome by slightly modifying the expressions for the stresses, so as to make this contribution to the energy vanish. . .".

However, the modifications made to the stress components were not given and have, in fact, been the subject of considerable speculation over the years since this paper was published. For example, some researchers [6,7] have claimed agreement with Eq. (1), while others [8,9] have advocated Eq. (2) as the correct result.

In a careful reworking of the energy calculations, Eftis and Jones [5] have shown that the expression for U_a assumes the form

$$U_a = \frac{\sigma^2 \pi (1+\nu) a^2}{4E}[1+k(2-\kappa)], \tag{3}$$

which reduces to Eq. (1) when k=1 for the equal tension-tension boundary conditions assumed by Griffith. If Eq. (3) is then employed in the fracture condition established by Griffith, namely that

$$\frac{\partial(\Gamma - U)}{\partial a} = 0, \tag{4}$$

where the surface energy, $\Gamma = 4\gamma a$, it follows that the critical stress, σ_c, is given by

$$\sigma_c = \left(\frac{8E\gamma}{\pi a}\left[\frac{1}{(3\nu-1)k+(1+\nu)}\right]\right)^{\frac{1}{2}} \tag{5}$$

for plane stress conditions, and

$$\sigma_c = \left(\frac{8E\gamma}{\pi a(1+\nu)}\left[\frac{1}{1+k(4\nu-1)}\right]\right)^{\frac{1}{2}} \tag{6}$$

for plane strain conditions. By comparison the "corrected" value of σ_c obtained by Griffith [2] is

$$\sigma_c = \left(\frac{2E\gamma}{\pi a}\right)^{\frac{1}{2}}, \tag{7}$$

for plane stress conditions, which is clearly independent of the biaxiality ration, k, and Poisson's ration, ν.

The results of some biaxial fracture toughness tests on glass tubes published by Griffith [1] are of considerable interest since biaxial applied loads did exist in his experiments. Therefore, it was possible to plot Griffith's critical stress data as a function of applied load biaxiality and compare the results with Eqs. (5) and (7). These comparisons are presented in Fig. 2, where it is quite evident that Eq. (5) provides a considerably better fit to the data than Eq. (7).

The form of Eqs. (5) and (6) indicates clearly that the behavior of σ_c versus k will also be a function of Poisson's ratio. It was shown by Eftis and Jones [5] that for materials having Poisson's ratios greater than 0.33 for plane stress conditions, the predicted critical stress will decrease with increasing k, while for ν less than 0.33, the predicted critical stress will increase with increasing k. This behavior is illustrated in Fig. 3. Another indication of the validity of these results is presented in Fig. 4, which shows a series of fracture toughness test results on PMMA sheets that were published by Radon and Leevers [10]. These results as well as the tests performed by Griffith represent a tentative confirmation of the validity of Eqs. (3), (5), and (6). However, the scatter in the data and the weakness in their variations with respect to k render the confirmations shown in Figs. 2 and 4 less than conclusive. Therefore, additional data is needed for eventual confirmation or rejection of these predictions and one of the objectives of the experimental portion of this project will be to provide such data.

Fatigue Crack Growth Rate Studies

The purpose of the initial phase of this study was to perform a careful study of existing publications concerned with effects of biaxial loads on the fatigue crack growth rates. In addition to the study by Liu and Dittmer [5], which was also supported by the Air Force, a number of papers have been identified which have addressed some aspects of the problem [11-15]. The subsequent study of these and other papers has led to the following conclusions:

(i) Very little analytical work has been done because the heavy reliance on the semi-empirical crack growth laws developed by Paris and others has led to the accumulation of a large amount of data correlated with the relation

$$\frac{da}{dN} = C(\Delta K)^n . \qquad (8)$$

(ii) Since it was shown earlier in this research program that the stress intensity factor, K, is independent of load biaxiality for the flat crack geometry, the da/dN versus K data could not be expected to properly account for load biaxiality, if it were indeed a factor affecting the fatigue crack growth rates.

(iii) Widely conflicting trends of the effect of load biaxiality on da/dN have been published in which increasing load biaxiality caused increased, decreased or negligible effects on the fatigue crack growth rates.

(iv) No other procedures for incorporating load biaxiality effects into the fatigue crack growth rate data have been published.

As a result of the current state of confusion about the effects of biaxial loads on da/dN, it was decided that some data would be generated under this research program and it would then be examined and correlated with other published results. It is expected that the results of such considerations will be included in the final report.

SUMMARY OF EXPERIMENTAL PROGRESS

During the third year of this grant, considerable progress was made in all of the experimental areas outlined in the proposal. Six additional fracture toughness tests were performed on plexiglass sheets having flat cracks aligned with one of the load axes. These data were intended to be combined with prior test results on the same material to determine whether a more definite trend of the effect of applied load biaxiality on the breaking strength (or fracture toughness) could be identified. Two biaxial test series have also been performed on specimens of 7075-T6 in which the cracks were oriented at 45° to either of the load axes. Biaxial load ratios of 0, 0.25, 0.5, and 1.0 were employed for these tests. In addition, a series of four fatigue crack growth rate tests were performed on 7075-T6 specimens with the crack aligned with one of the load axes. The biaxiality ratios for these tests were k = 0, 0.5, 1.0, and 1.5.

Static Biaxial Tests on Plexiglass

The results of fracture tests performed on plexiglass sheets during the first year of this grant showed that the breaking load was relatively independent of k and there was a considerable amount of scatter in the data. However, the results presented in Fig. 4 indicate that a considerable amount of scatter is apparently inherent in the fracture toughness testing of this material (plexiglass is a generic name for polymethylmethacrylate). Therefore, it was decided to perform some

additional fracture toughness tests on plexiglass specimens having the same geometry as those tested during the first year (flat center cracks aligned with one load axis). The test procedures followed were also the same as in the earlier tests: (i) The cracks were made by initial filing, and then a razor blade was forced in to initiate and grow the crack; (ii) A ramp function was applied without interruption so that the specimen would fracture in approximately 50 seconds; (iii) The load versus displacement curves were recorded on an x-y recorder; and (iv) The peak load was also recorded on a special meter. The range of load biaxialities for these tests was increased to $-2.0 \leq k \leq 2.5$.

The breaking loads of all plexiglass specimens were combined and are shown as a function of k in Fig. 5, where the most recent six test points are shown as squares while the tests performed earlier are shown as circles. It is seen that the addition of the new test results does not contribute to the appearance of an identifiable trend except for k values greater than zero. The critical load values decrease quickly with increasingly negative k values, which does not appear to be part of the same trend line as the positive k data. It is quite possible that some form of buckling instability may be causing the low breaking loads in the tension-compression tests. However, the results for the positive k values do appear to show a decreasing trend in breaking loads as the k values increased. Further discussion of this matter will be presented in the final report for this grant.

In order to obtain further insight into the significance of these results, the data from Fig. 5 were converted to K_{Ic} values and plotted in Fig. 6. At first glance these data appear to exhibit greater scatter than the critical loads, but this is due primarily to the expanded ordinate scale. For Fig. 5 most data fall between 0.7 and 1.0 for a variation of approximately 40-45 percent of the base line value while the results in Fig. 6 mostly range from 1.5 to 1.8 for a variation of 20 percent of the base line value. The data for positive k values also show a definite decreasing trend with increasing k, in agreement with Fig. 4 since this material has a Poisson's ratio in the range 0.4 - 0.45.

Angle-Crack Tests

Since a crack in a structure subjected to biaxial loads will in general not be aligned with either of the principal loading directions, the effect of biaxial applied loads on an angle-cracked specimen is of considerable practical importance. Therefore, two series of four biaxial fracture tests were performed on 7075-T6 specimens, 0.063" thick, in which the crack was oriented at 45° to either of the load axes. Because of the symmetry of the specimen geometry it was not necessary to employ biaxiality ratios greater than 1.0, so values of k = 0, 0.25, 0.5, and 1.0 were employed for both test series. In one test series the primary (larger load) axis was aligned with the rolling direction while for the other series the primary axis was perpendicular to the rolling direction. Fig. 7 shows the broken specimens from the equal biaxial tests (k = 1.0) for

both test series, with the principal load axis horizontal in each case. In Fig. 7a the rolling direction was perpendicular to the principal loading axis and the crack exhibited some preference to propagate toward the rolling direction, rather than along the plane of the starter slot. In Fig. 7b the rolling direction was parallel to the principal loading axis and the crack again exhibited a preference to propagate in a direction between the rolling direction and the plane of the starter slot.

For these tests, the load versus displacement for the principal axis was plotted continuously using an x-y recorder, and the loading ramp function was interrupted periodically for the purpose of recording the load and displacement values on each axis. The critical load along the principal axis was also recorded using a special meter. In order to obtain an estimate of the effect of load biaxiality on this geometry, the opening-mode plane-stress fracture toughness, K_c, was evaluated for each test by resolving the components of the peak loads along both load axes to a direction perpendicular to the starter notch. The two load components were then added and used to evaluate K_c. The results of these calculations are presented in Fig. 8, where it is seen that K_c is strongly dependent upon k. Both sets of data provided similar results, with the K_c values associated with cracking more perpendicular to the rolling direction being slightly higher than the others. In both cases the K_c values nearly doubled as the load biaxiality increased from zero to one.

Fatigue Crack Growth Rate Tests

During the second year of this grant, four biaxial fatigue crack growth rate tests were performed on 2024-T3 aluminum sheets, 0.063 "thick, in which the center cracks were oriented with the center cracks were oriented with one of the load axes. Two tests were performed on specimens with the cracks perpendicular to the rolling direction (k = 0, 1.0) and two with cracks parallel to the rolling direction (k = 0, 1.0). The specimens were of the same design as for the static tests and the loads were varied in a sinusoidal manner, with both axes being loaded in phase. The test frequency was 12 hz and, with the exception of the first test (Fig. 9), the crack growth measurements were made while the test was running. The load ratio , $R = \sigma_{min}/\sigma_{max}$, was maintained at 0.1 for all tests. An arbitrary initial cyclic load level was imposed on the specimen until fatigue cracks initiated from the starter notches and the load level was then reduced until a reasonable crack growth rate was obtained. This cyclic load level was then maintained until the specimen fractured. The crack size was recorded as a function of the number of cycles and from these data calculations were made for the crack growth rate $\frac{da}{dN}$ as a function of the applied stress intensity range ΔK.

In the last Interim Scientific Report [3] it was reported that for the first two tests (Figs. 9 and 10) the fatigue crack growth rate decreased by a factor of approximately one-half as the load biaxiality was increased from k=0 to k=1.0. However, for the second pair of tests with the crack parallel to the

rolling direction, the fatigue crack growth rate decreased only about 25 percent as k increased from 0 to 1.0. Because of the lack of time the data was not reduced and plotted in the prior report. The initial data reduction and plotting has been completed and the results for the first four tests are presented in Figs. 9-12. It can be seen that the results at one ΔK value presented in the earlier progress report were typical over the entire range of ΔK values tested. It is planned to make some further examination of these data, including some curve fitting, and include these results in the final report.

In order to obtain more data about the effect of biaxial loads on fatigue crack growth rates, four additional tests were performed on 7075-T6 aluminum sheets 0.063 inch thick. The geometry was the same as the previous four tests except that the starter notch was considerably shorter so that more data could be collected. Also for these tests, after an initial set of data were taken at a low crack growth rate, the load was increased in several steps so that a larger range of ΔK values could be examined. The test frequency for these tests was varied from 15 to 10 as the test progressed and the crack growth rates increased. In all four of these tests the crack was parallel to the rolling direction and the k values selected were 0, 0.5, 1.0 and 1.5, as indicated in Figs. 13-16. These results show that for 2075-T6 as well as for 2024-T3, increasing load biaxiality causes a significant decrease in the fatigue crack growth rate. The crack growth rate decreased significantly as k increased, indicating that this problem needs further exploration.

The results shown in Fig. 16 were quite limited since the high k value caused one of the loading tangs parallel to the crack to break while the crack size was still small. It is planned that these data will be further studied and presented in detail in the final report for this grant.

LIST OF REFERENCES

[1] A. A. Griffith, The Phenomena of Rupture and Flow in Solids. Phil. Trans. Roy. Soc., London, A, V. 221, pp. 163-198, 1921.

[2] A. A. Griffith, The Theory of Rupture. Proc. First Int. Cong. Appl. Mech., Delft, pp. 55-63, 1924.

[3] D. L. Jones and J. Eftis, Fracture and Fatigue Characterization of Aircraft Structural Materials Under Biaxial Loading. Interim Scientific Report, AFOSR, October 1977-1978.

[4] A. F. Liu and D. F. Dittmer, Effect of Multiaxial Loading on Crack Growth. AFFDL-TR-78-175, 1978.

[5] J. Eftis and D. L. Jones, On the Fracture Stress of the Griffith Crack Problem and its Relation to Load Biaxiality. Submitted for publication.

[6] J. L. Swedlow, on Griffith's Theory of Fracture. Int. J. Fract. Mech., V. 1, pp. 210-216, 1965.

[7] K. Z. Wolf, Zur Bruch Theories von A. Griffith. Angew. Math. Mech., V. 3, pp. 107-112, 1923.

[8] A. J. M. Spencer, On the Energy of the Griffith Crack. Int. J. Eng. Sci., V. 3, pp. 441-449, 1965.

[9] G. C. Sih and H. Liebowitz, On the Griffith Energy Criterion for Brittle Fracture. Int. J. Solids Struct., V. 3, pp. 1-22, 1967.

[10] J. C. Radon and P. S. Leevers, Fracture Toughness of PMMA Under Biaxial Stress. Fracture, 1977, V. 3, ICF4, Waterloo, Canada, pp. 1113-1118, 1977.

[11] J. J. Kibler and R. Roberts, The Effect of Biaxial Stresses on Fatigue and Fracture, J. Eng. Industry, pp. 727-734, 1970.

[12] P. S. Leevers, J. C. Radon and L. E. Culver, Crack Growth in Plastic Panels Under Biaxial Stress. Polymer, V. 17, pp. 627-632, 1976.

[13] C. D. Hopper and K. J. Miller, Fatigue Crack Propagation in Biaxial Stress Fields. J. Strain Analysis, V. 12, pp. 23-28, 1977.

[14] N. J. I. Adams, Some Comments on the Effect of Biaxial Stress on Fatigue Crack Growth and Fracture. Eng. Fract. Mech., V. 5, pp. 983-991, 1973.

[15] K. Ogura, K. Ohji and Y. Ohkubo, Fatigue Crack Growth Under Biaxial Loading. Int. J. Fract., V. 10, pp. 609-610, 1974.

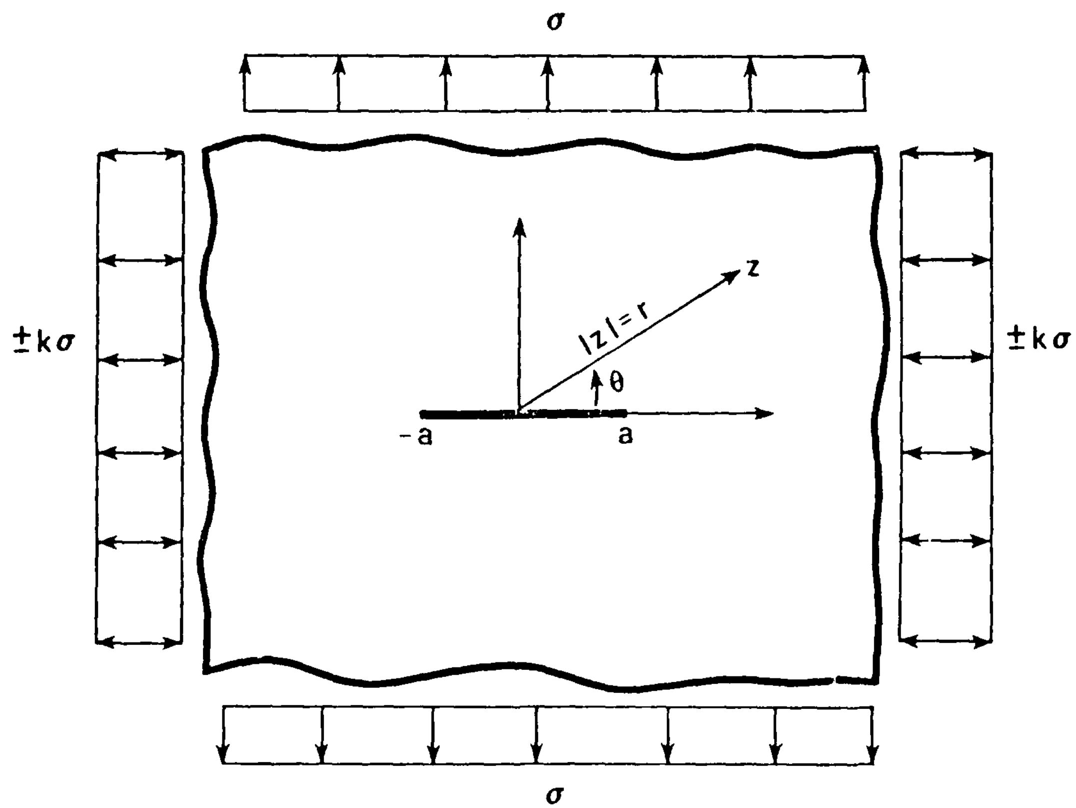


Fig. 1. Crack geometry and boundary tractions.

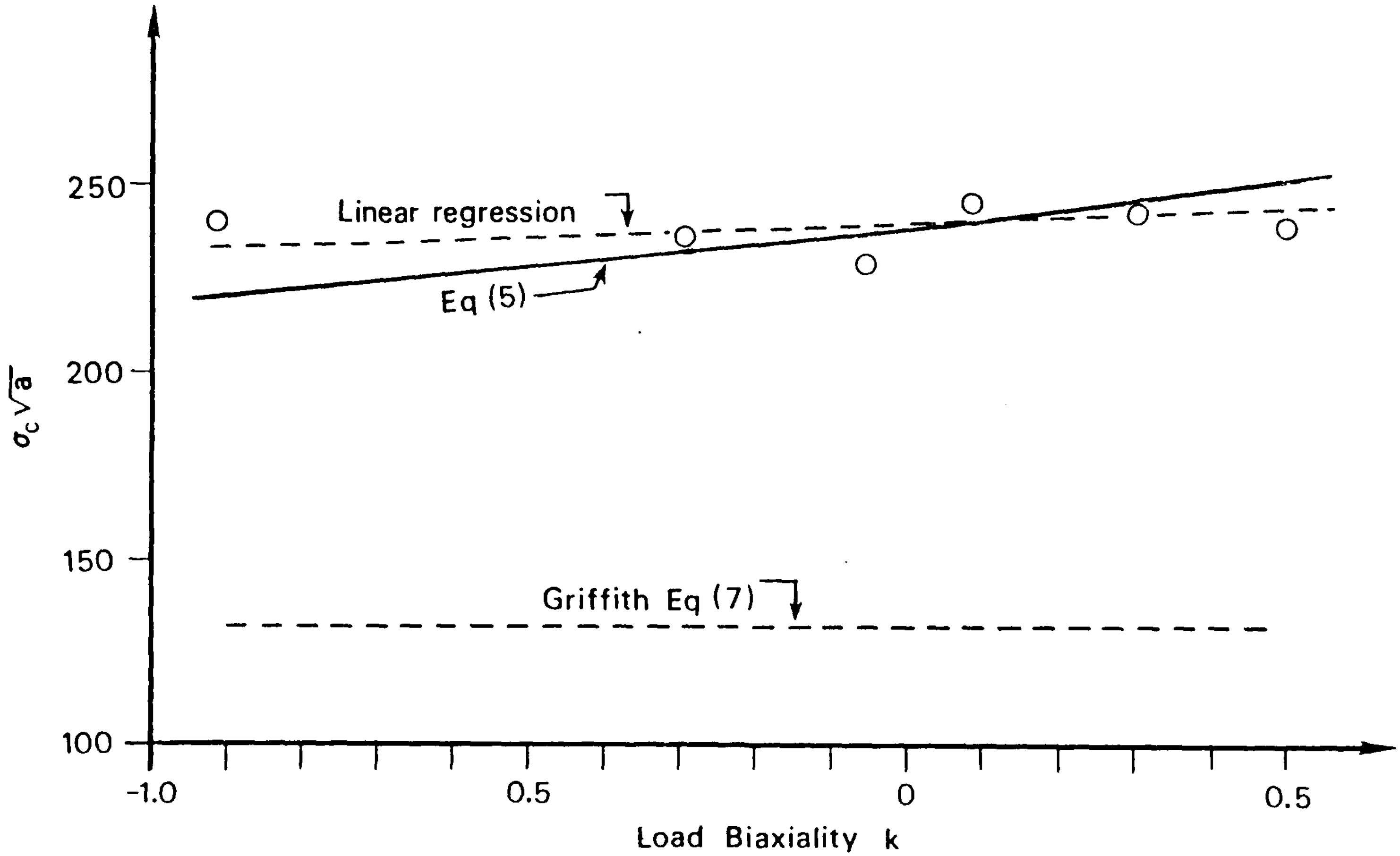


Fig. 2. Breaking strength of cracked circular glass tubes.

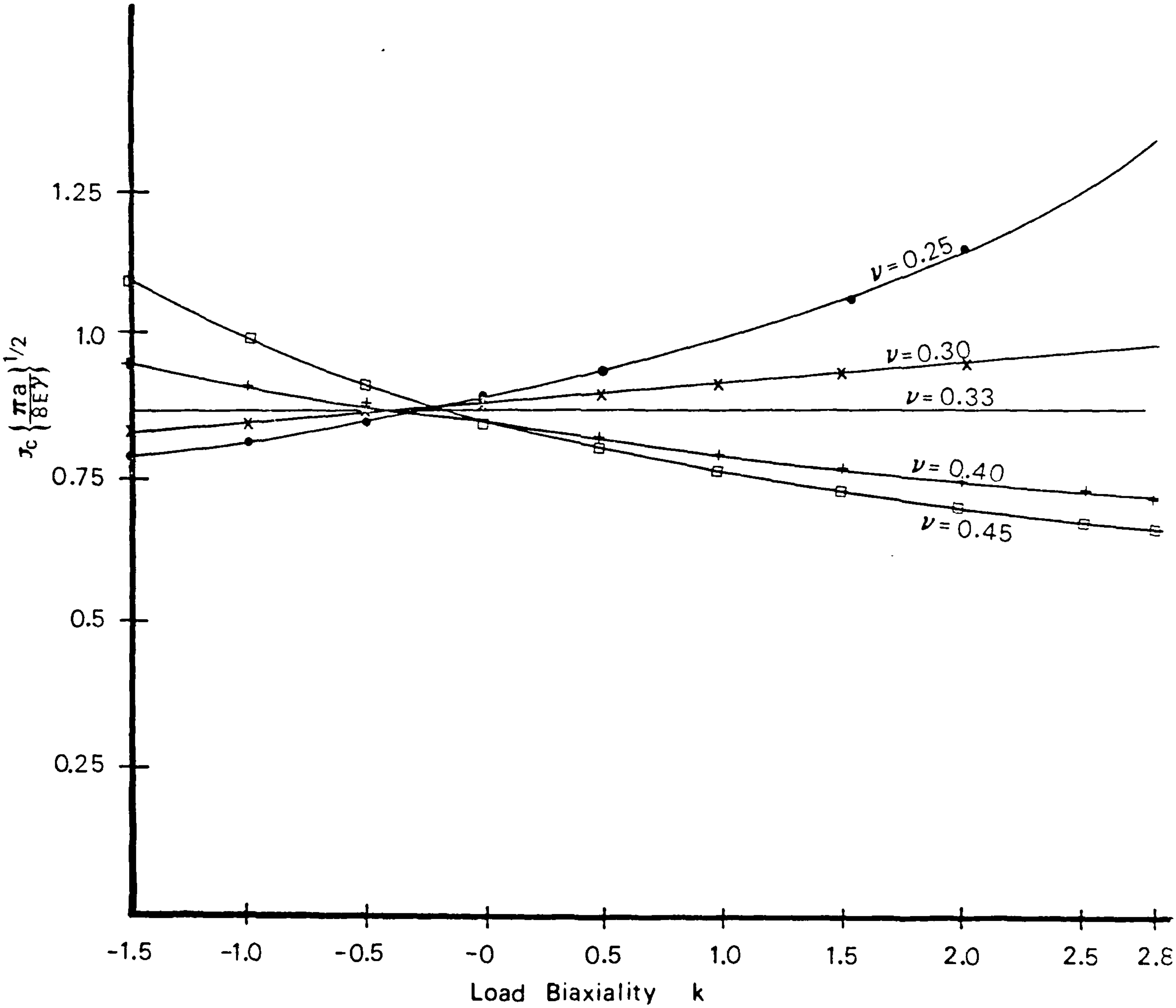


Fig. 3. Critical stress variation with load biaxiality (plane stress).

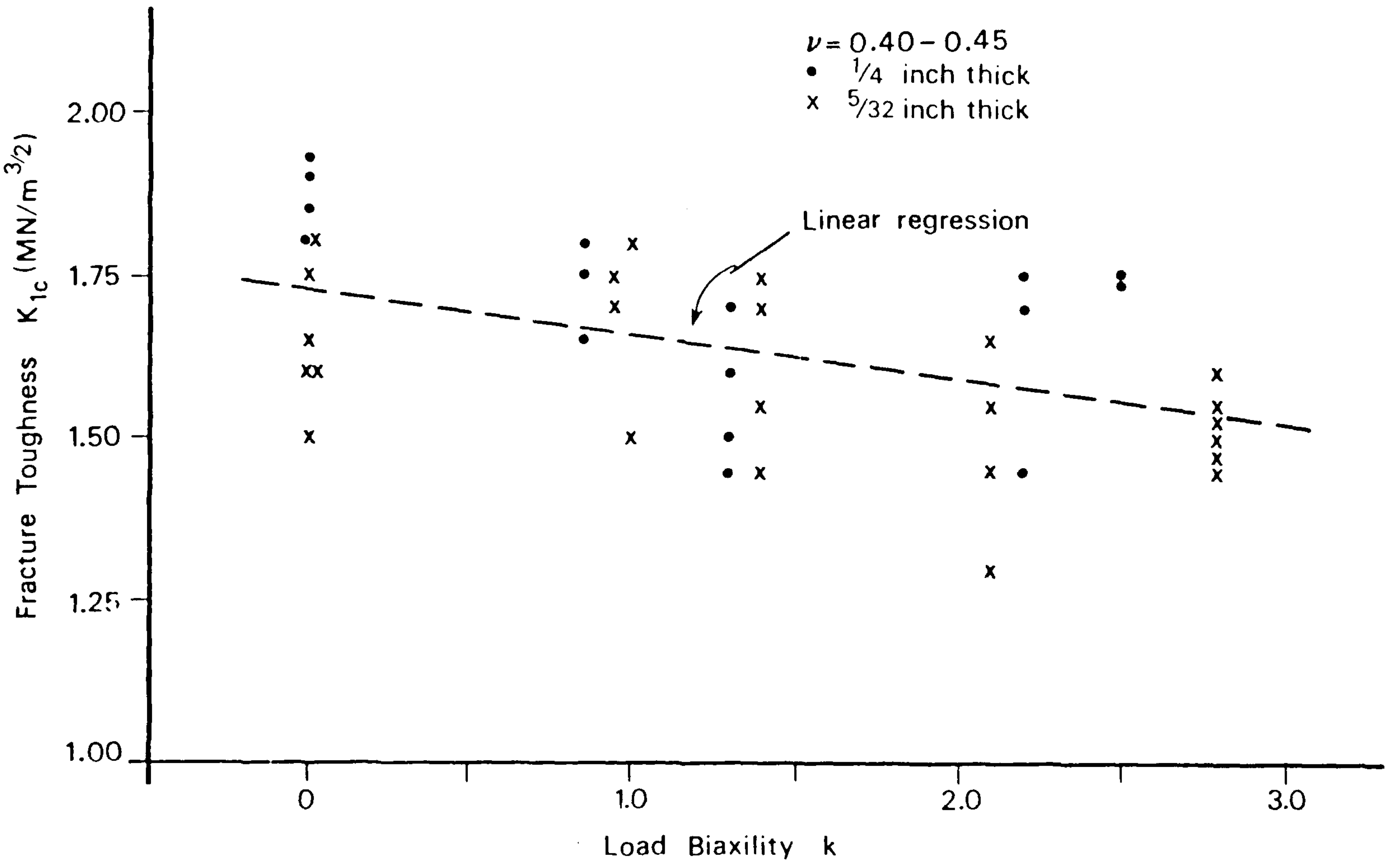


Fig. 4. Fracture toughness (fracture load) for Polymethylmethacrylate (PMMA) sheets.

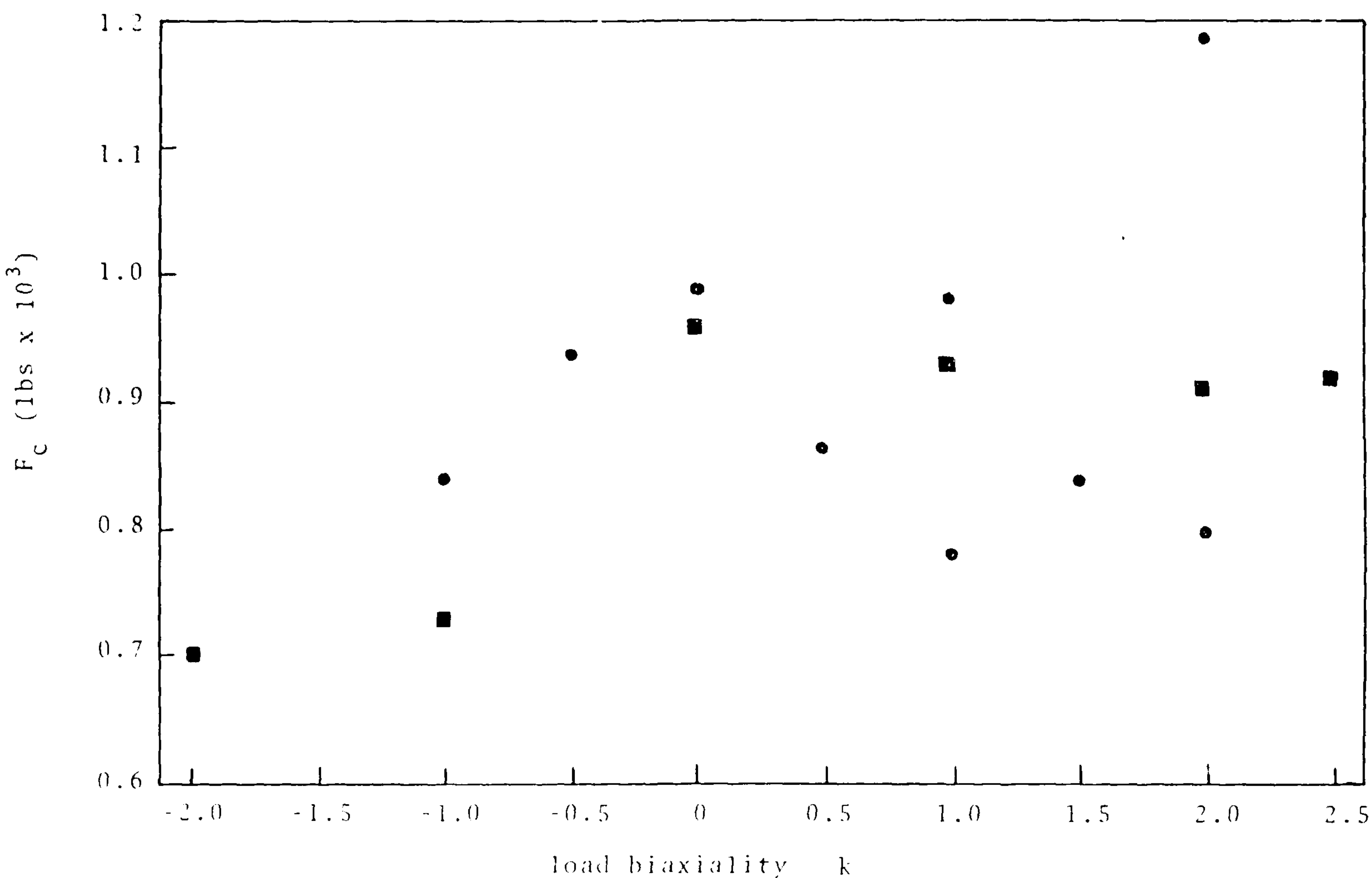


Fig. 5. Critical breaking load, F_c, of center-cracked plexiglass sheets, ¼" thick.

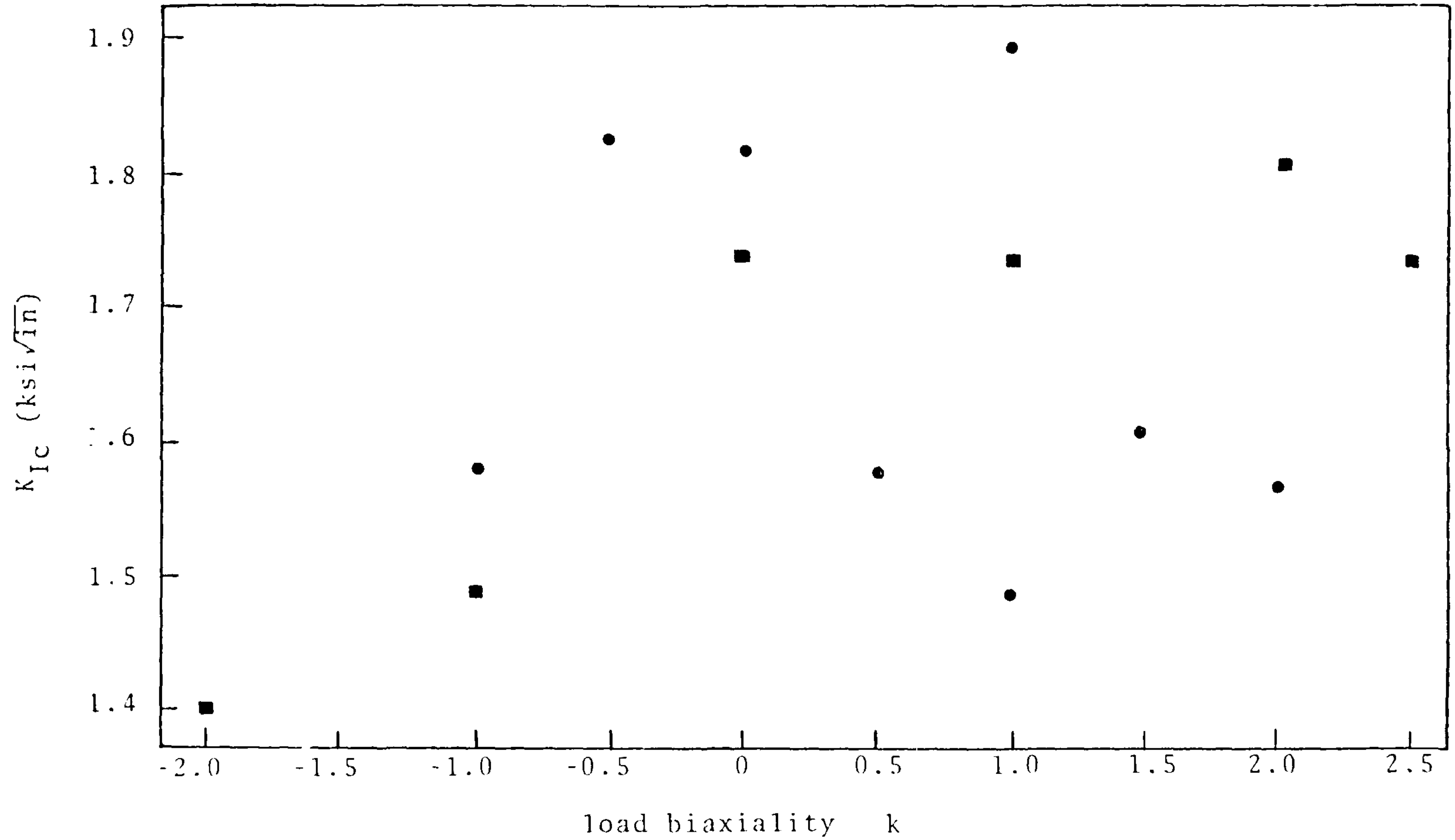
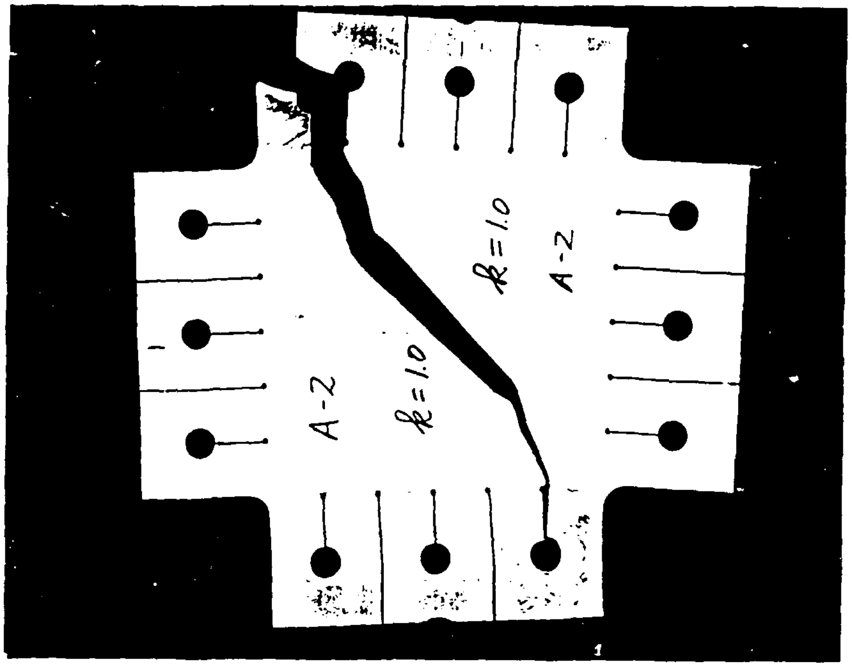
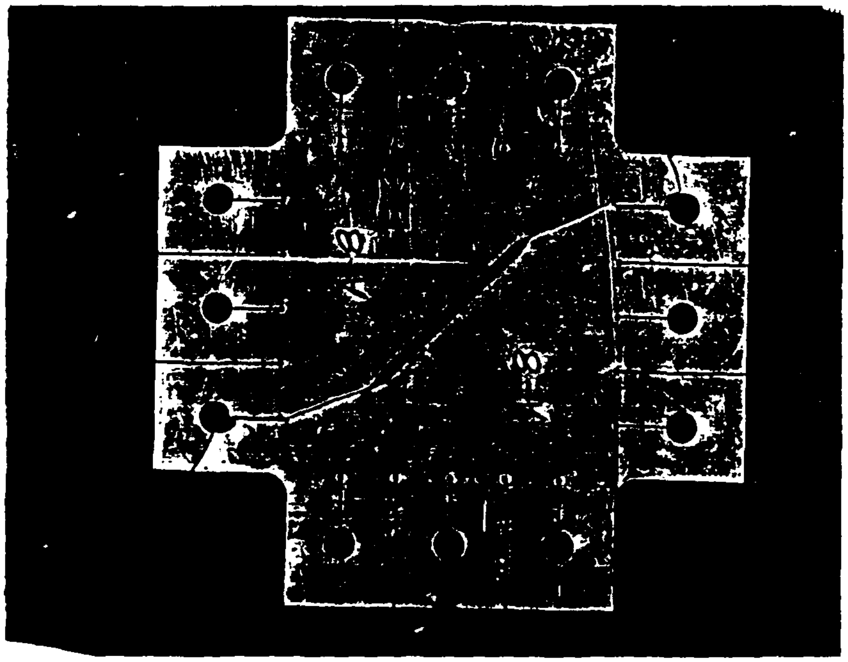


Fig. 6. Plane strain fracture toughness of center-cracked plexiglass sheets, ¼" thick.



(a) Principal axis perpendicular to rolling direction.



(b) Principal axis parallel to rolling direction.

Fig. 7. Photographs of fractured angle-crack specimens made of 7075-T6 aluminum, 0.063" thick, k = 1.0.

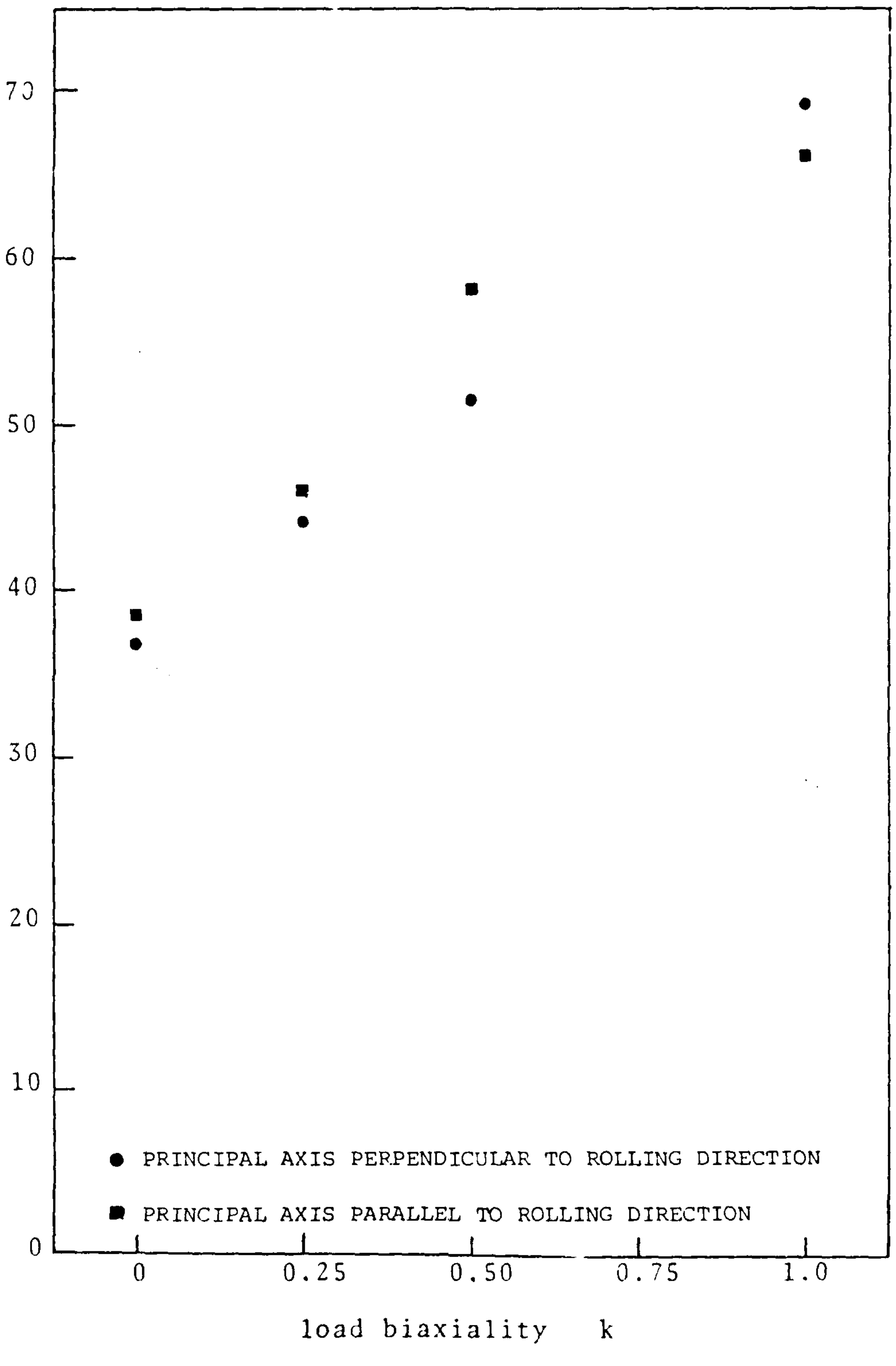


Fig. 8. Fracture toughness as a function of load-biaxiality for angle-cracked specimens.

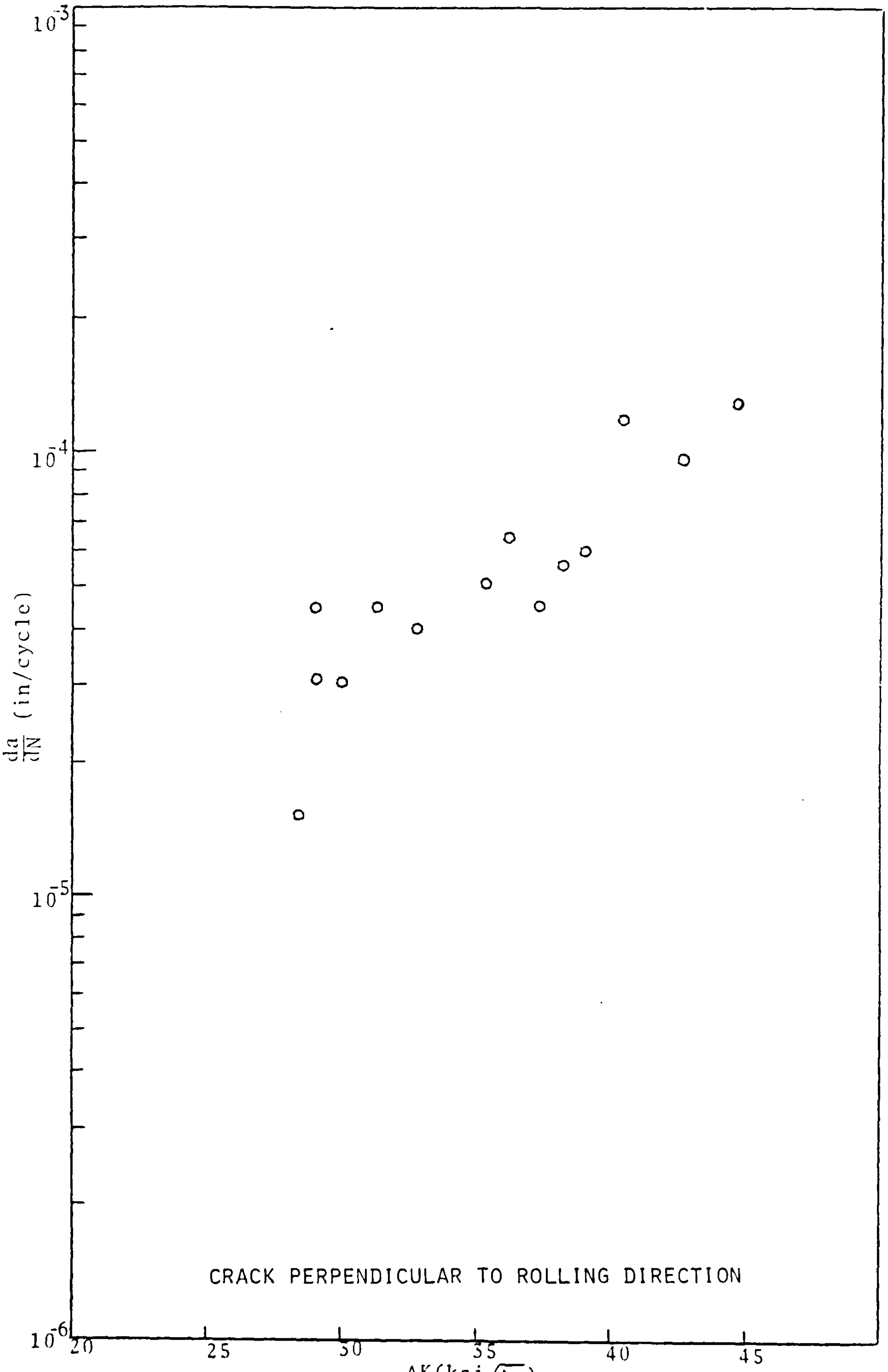


Fig. 9. Fatigue crack growth rate data for 2024-T3, k=0.

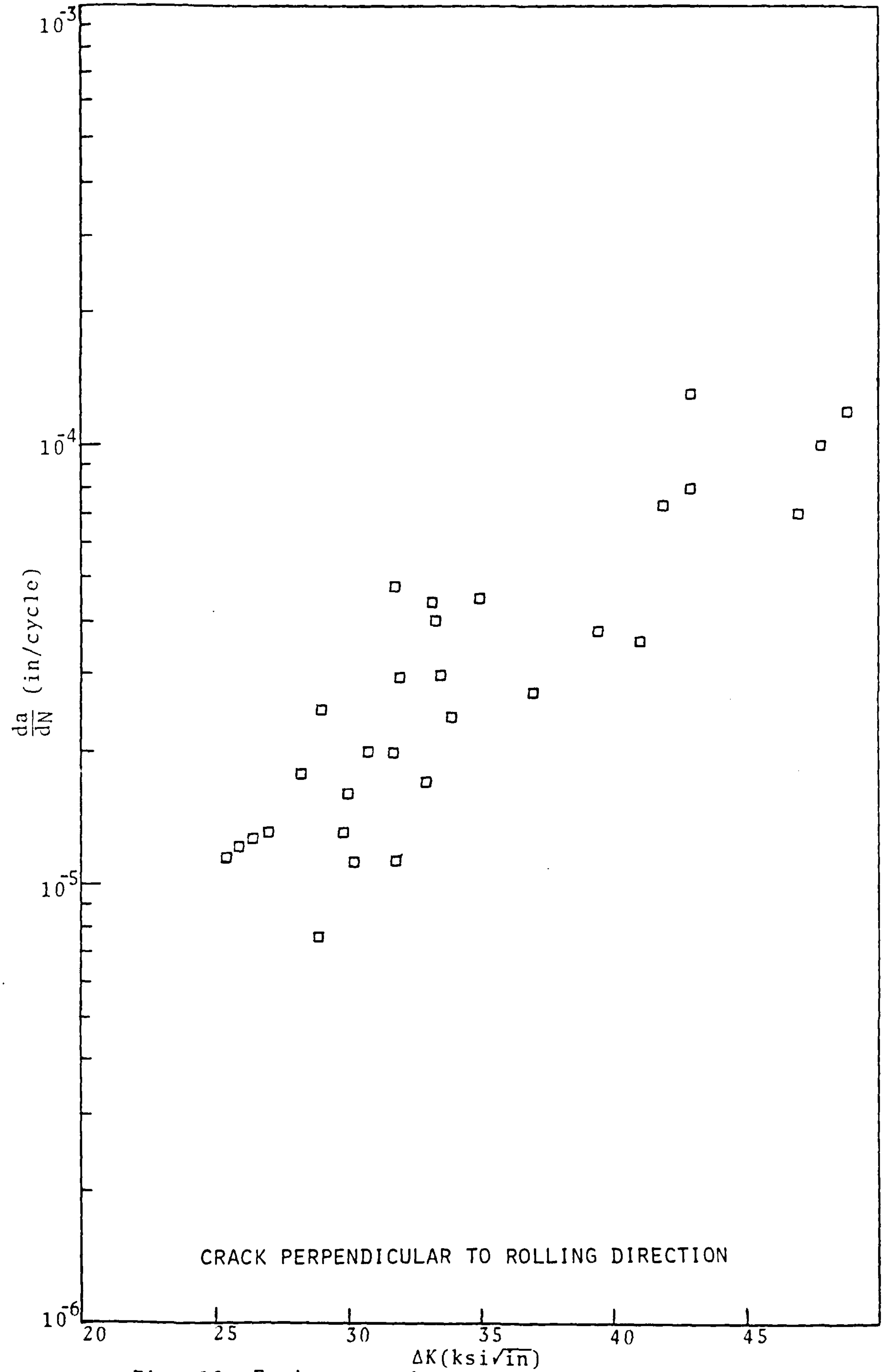


Fig. 10. Fatigue crack growth rate data for 2024-T3, k=1.

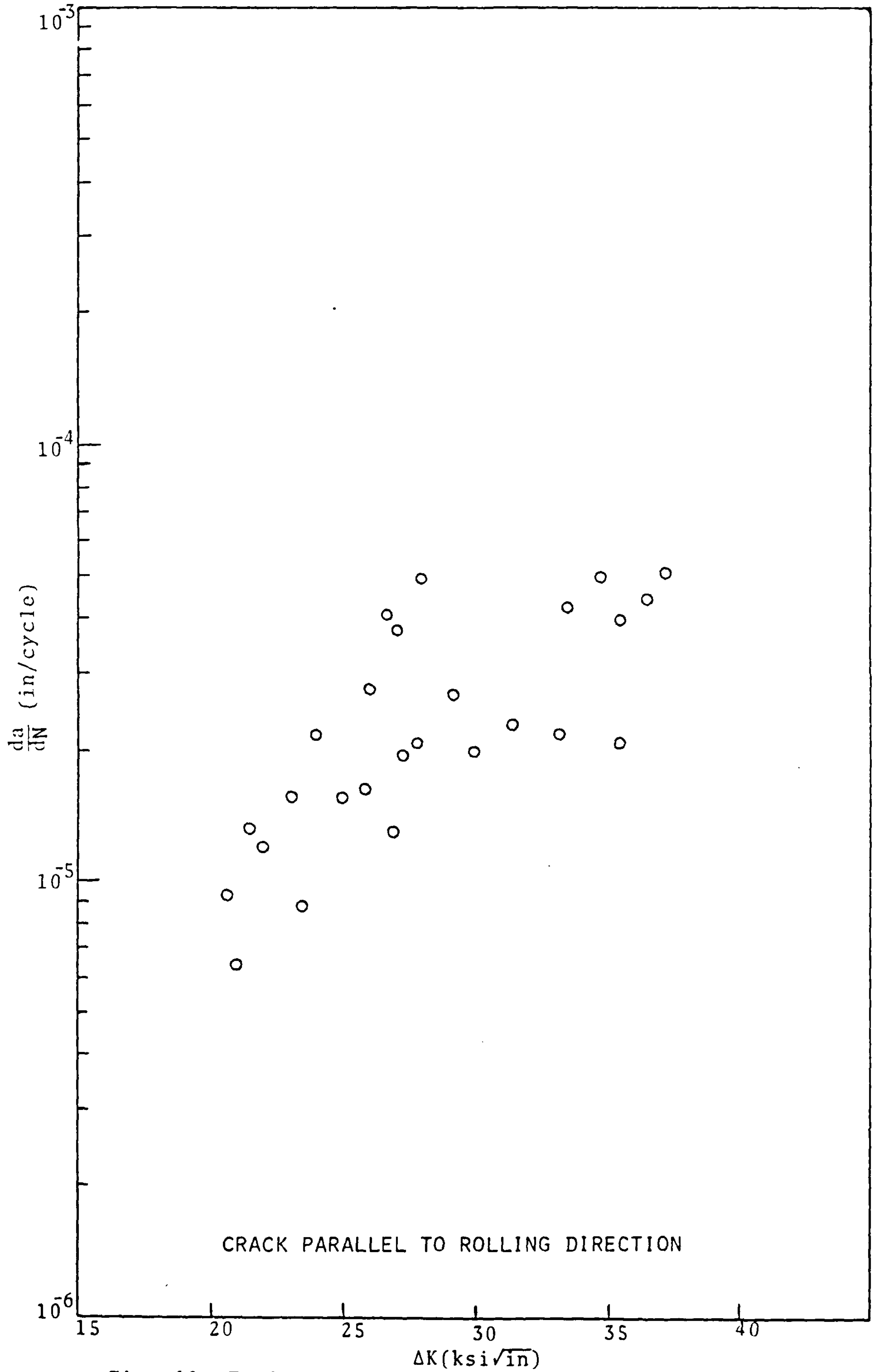


Fig. 11. Fatigue crack growth rate data for 2024-T3, k=0

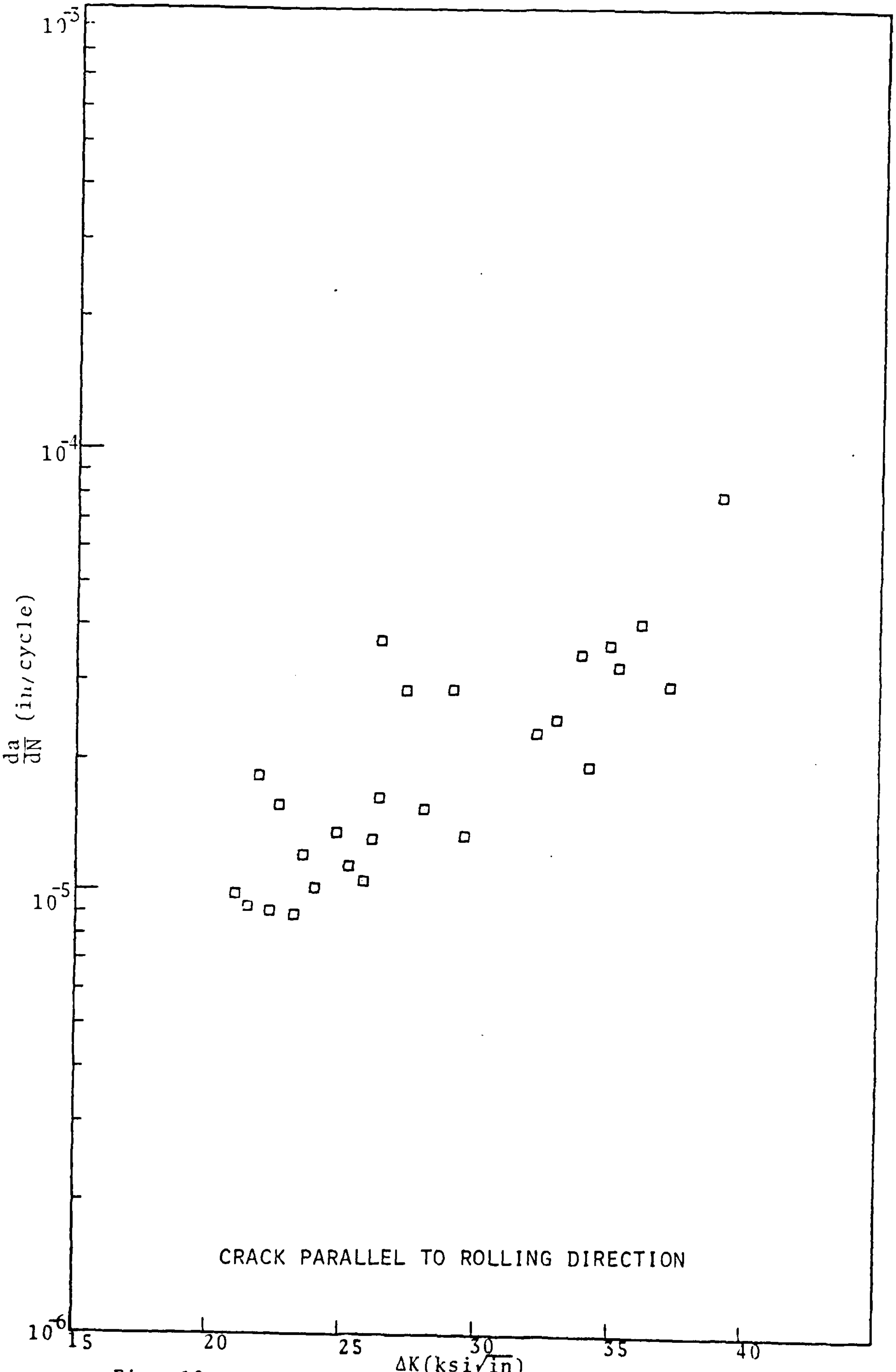


Fig. 12. Fatigue crack growth rate data for 2024-T3 k=1

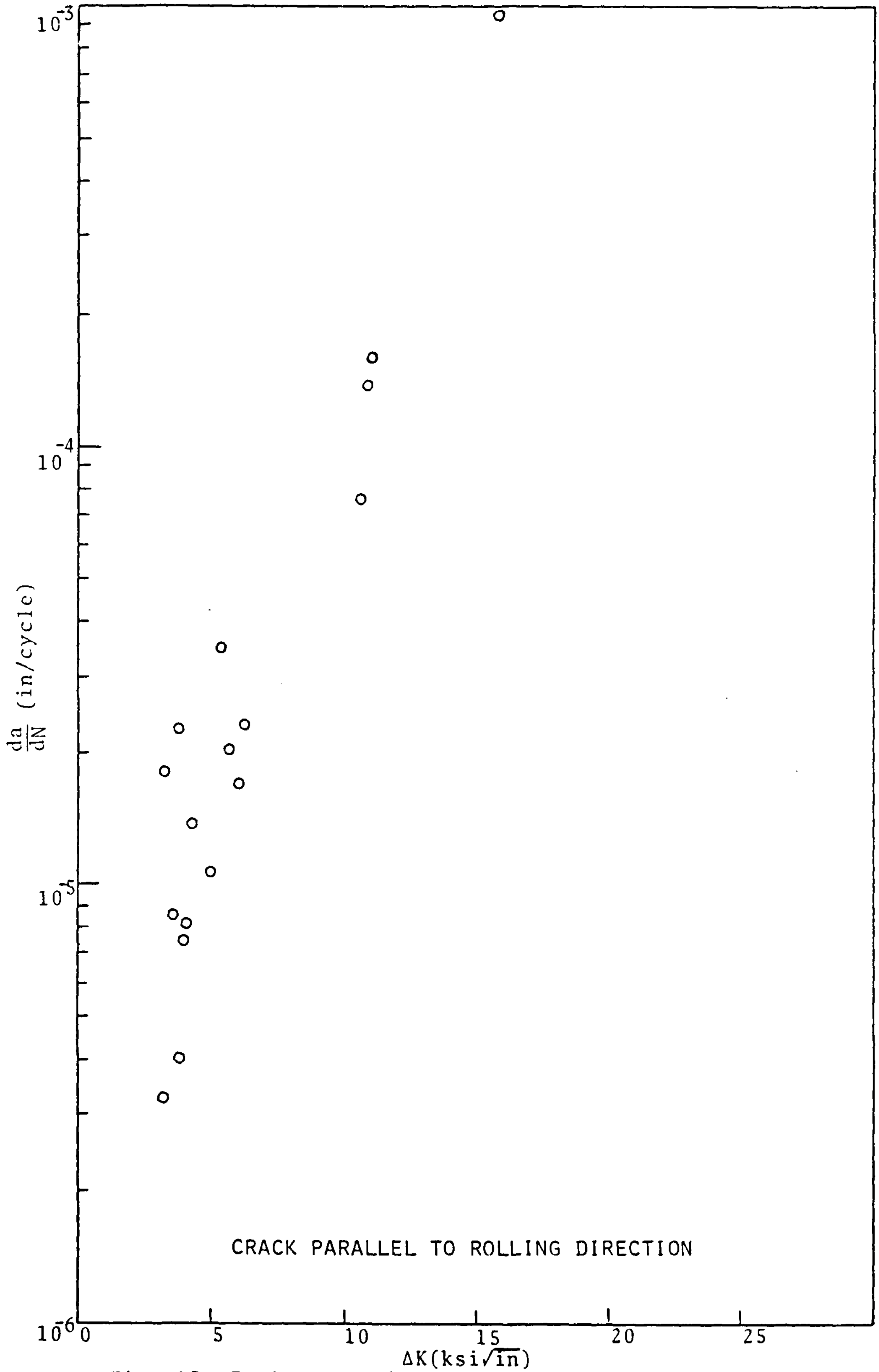


Fig. 13. Fatigue crack growth rate data for 7075-T6, k=0.

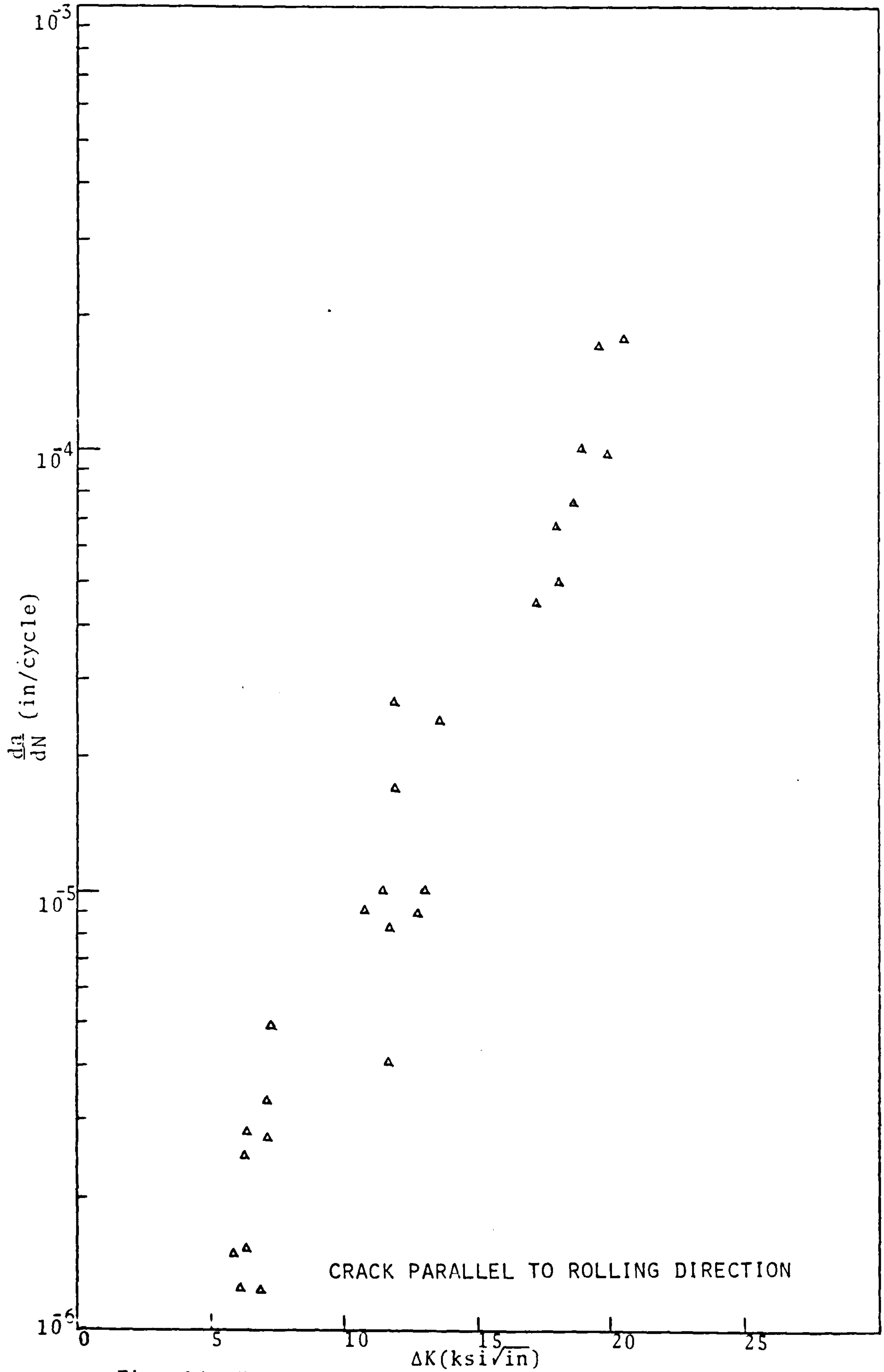


Fig. 14. Fatigue crack growth rate data for 7075-T6, k=0.5.

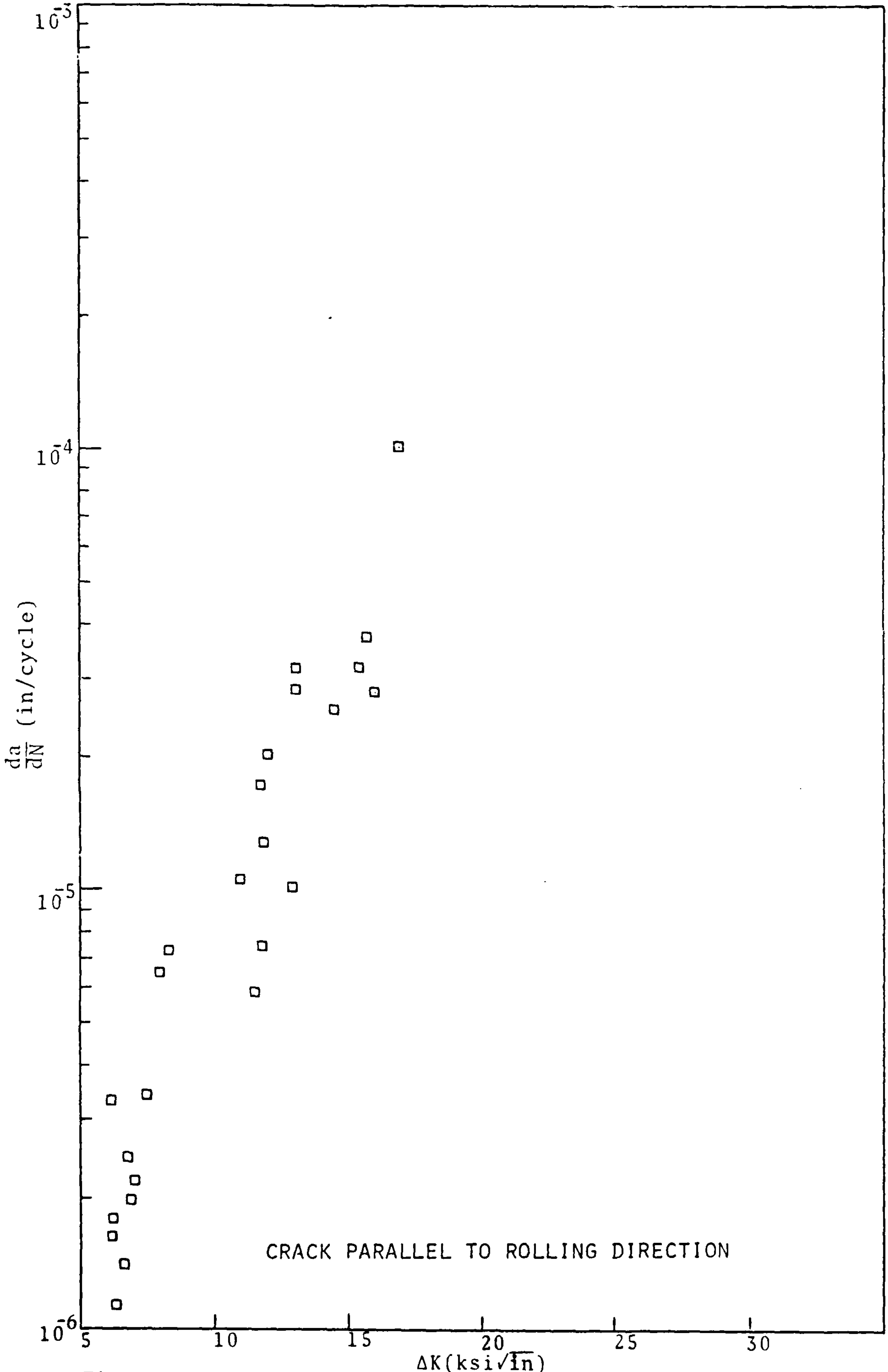


Fig. 15. Fatigue crack growth rate data for 7075-T6, k=1.0.

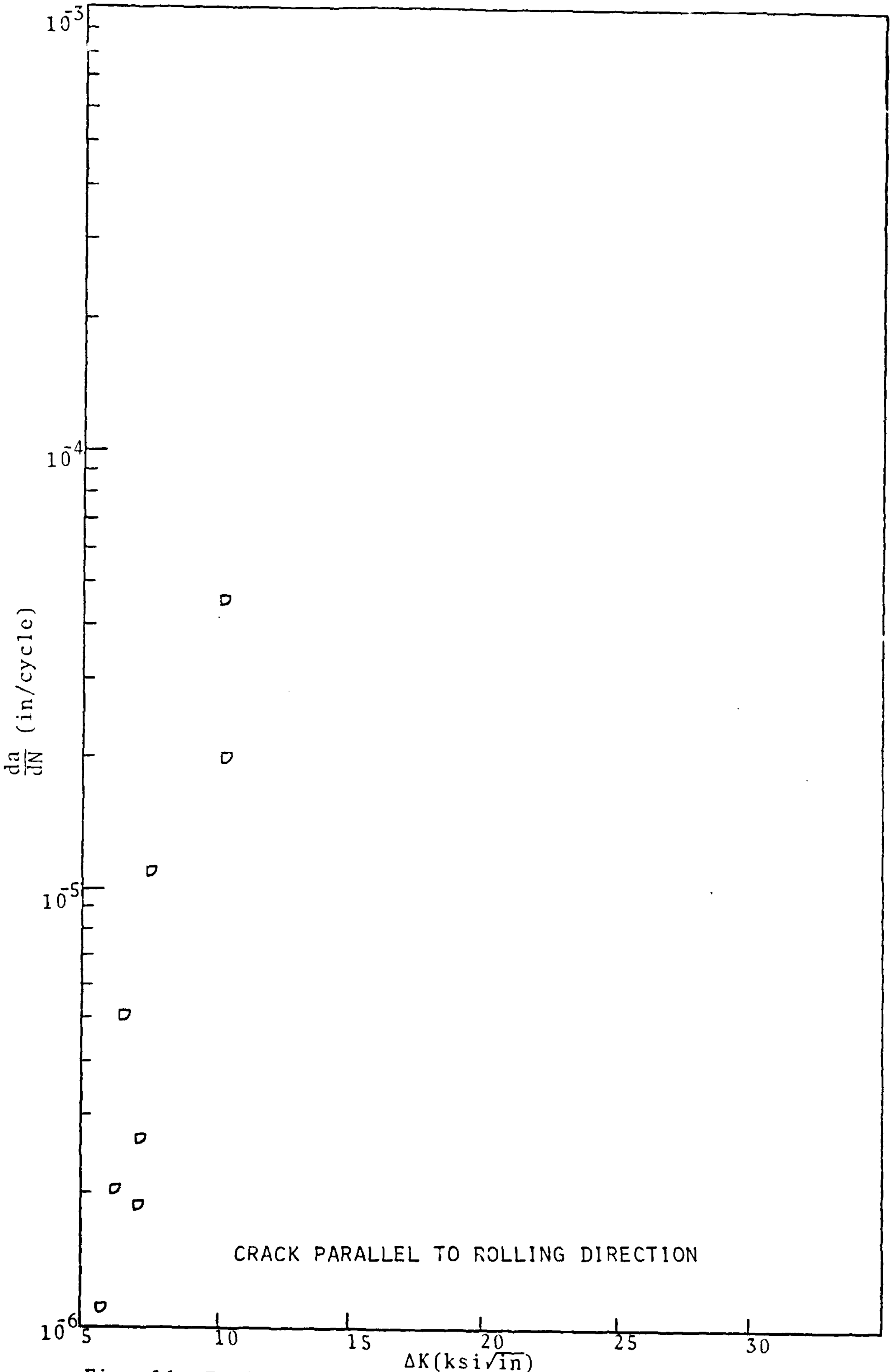


Fig. 16. Fatigue crack growth rate data for 7075-T6, k=1.5.